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Field Measurements of the Influence of Bubbles on the Inherent Optical Properties of the Upper Ocean

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14. ABSTRACT

This report describes the research performed on behalf of the Office of Naval Research (grant #N00014-02-1-0190) to understand the influence of air-sea interaction processes on hyperspectral remote-sensing of the ocean's surface. The Hyperspectral Coupled Ocean Dynamics Experiment (HYCODE) and Monte Carlo Radiative model were used to investigate these processes, as well newly refined acoustic techniques. A byproduct of this research will be models to correct for bubble mediated effects in measured hyperspectral light fields using wind and wave information. The program also presented an opportunity to develop techniques for inverting remotely-sensed hyperspectral imagery for in-situ bubble concentrations.

15. SUBJECT TERMS
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LONG-TERM GOALS

The long term goals of this project are to better understand the influence of air-sea interaction processes on hyperspectral remote-sensing of the ocean's surface.

OBJECTIVES

This research program is concerned with understanding the role of bubbles injected by breaking waves in modifying the inherent optical properties (IOPs) of the upper ocean. Surface-layer oceanographic phenomena such as turbulent mixing are also addressed in the investigation as they are known to play a large role in determining the depth to which bubble clouds penetrate, the bubble residence times, and the bubble size distributions. The data collected during this program is providing the necessary information for the development of physical models of the evolution of bubbles in the surface wave layer based on wind and wave forcing. Models of remote sensing reflectance are being extended from these synoptically forced bubble models to understand the role of bubbles in modifying the optical properties of the upper ocean. A byproduct of this research will be models to correct for bubble mediated effects in measured hyperspectral light fields using wind and wave information. The program also presents the opportunity to develop techniques for inverting remotely-sensed hyperspectral imagery for in-situ bubble concentrations.

APPROACH

As part of the Hyperspectral Coupled Ocean Dynamics Experiment (HYCODE), a field sampling program was designed for measurements of bubbles and IOPs over a range of sea states. The variability of the bubble field that results from wave breaking necessitates that the bubble and optical field be sampled with sufficient temporal and spatial resolution. Acoustic techniques that have been refined over the last decade (Terrill & Melville, 2000) are used for measuring the bubbles in conjunction with optical measurements to directly measure the bubble field and the resulting optical scattering. A Monte-Carlo Radiative transfer model has also been developed and applied to the problem of computing remote sensing reflectance from IOPs that are heterogeneous in space. Results from the modeling are being coupled with the physical measurements to provide insight on how to extend the results to satellite-based remote sensing assets which have large pixel footprints that would integrate over many different spatial patches of bubbles.

WORK COMPLETED

The first few years of this program focused on developing measurement capabilities, data collection, and data analysis, our efforts are now focused on advanced analysis, modeling, and publication efforts. Details related to the accomplishments associated with the field intensive effort in the earlier years of the program have been summarized in earlier reviews. These efforts have included field studies conducted at the LEO-15 site off the coast of Tuckerton, New Jersey and at site offshore the windward coast of Oahu, Hawaii using the Research Platform FLIP. The contrast in the optical complexity of the waters has provided an opportunity to study bubble related phenomena in both case 1 and case 2 waters. New Jersey's relatively benign sea conditions and turbid water prompted us to examine other sites which would allow us to examine the influence of bubbles on marine light fields in clear waters. However, despite the turbid waters experienced in New Jersey, we were able to obtain a wealth of information on the impact of dense of bubble clouds on near surface water IOPs. This data was obtained using time series obtained from an air-sea interaction buoy that was deployed with acoustic and optical sensors as well the use of a small boat that allowed us to measure the spatial scales of the bubble populations. Examples of the types of phenomena measured are illustrated in figures 1 and 2.

The opportunity to use FLIP offshore Hawaii was provided by ONR's support of the Rough Evaporation Duct (RED) Experiment. RED had complementary objectives to HYCODE in its need to measure surface waves and aerosol populations to better understand EM and EO propagation. Time series of IOPs and bubbles were again obtained by our group using optical and acoustic instruments. After our successes in New Jersey to measure bubble influences on IOPs, we expanded our measurement effort to also obtain a time series of the remote sensing reflectance using a suite of hyperspectral radiometers. These radiometers were deployed from the face boom of FLIP with consideration to prevent hull shading from influencing the measured water leaving radiancs. The multi-week time series provided us an opportunity to examine the variability of the remote sensing reflectance on short (O(1) second) time scales corresponding to breaking events and longer time scales that corresponded with wind events. Analysis efforts with the radiometer data focused on understanding trends in the measured reflectances. Central to this effort is the goal to separate the sky reflectance from the water leaving radiances which presumably would reflect the signature of bubbles during the higher sea states. While indeed the measured Lw/Ed (both sensors were above water) do scale with the sea state, removing sky reflection and sun glitter which covary with seastate proved difficult. Since the effects of sun glint can be minimized by choosing appropriate sun angles and removing saturated spectra, the sky reflection problem has proved difficult since the sky radiance distribution was not measured. The atmospheric correction algorithms that exist do have a wind speed dependence of the surface roughness, they have been designed primarily for satellite-based, kilometer sized pixels. For the O(1-5) m^2 spot size that we sampled, shortcomings in these algorithms becomes readily apparent. A known example of this is the ability to image ocean swell by a hyperspectral sensor such as PHILLs or AVIRIS, even after 'atmospheric corrections' have been applied which should account for the wind speed / surface roughness dependence. This is due in part to the statistical description attributed to the surface roughness which does not account for small scale variability. In the case of the ocean swell, the capillary waves responsible for reflecting the light are modulated by the longer period swell.

Our continuing work with a Monte-Carlo radiative transfer model to examine bubble mediated influences on underwater light fields a) examined the influence of forward and multiple light scatter in measuring IOPs in highly scattering environments and b) the computation of water leaving radiances in situations of dense clouds of bubbles. Our procedure in a) was to first compute volume scattering functions for six different density ranges of bubbles, as defined by their void fraction. Since the bubble size distribution evolves in time as a result of physical processes, the VSF will also be time dependent. We make the argument that bubble density can be considered as a proxy for the age of bubbles, whereby the size distribution evolves under the processes of bubble rise speed, bubble mixing, and gas dissolution. Results discussed in Piskozub et al (2004) presents the modeling results for a) and discusses the associated errors in measuring beam attenuation in scattering environments such as those found within bubble populations. One motivation for this work was to assist in our interpretation of the field measurements which measured light attenuation values of O(1-10)m^{-1} and higher within bubble clouds using a 10cm pathlength transmissometer.

To address b) a wide range of different, idealized bubble cloud densities and geometries (based upon field data) were modeled with the 3D codes. The model also allows us to examine the bubble influences as a function of both optical wavelength, chlorophyll concentration, or other background optical constituent. Work is currently underway to compare the output of these results with simplified 1-D, slab models of radiative transfer (eg – Hydrolight). Papers our currently undergoing internal review which describe the model and results from the modeling efforts

RESULTS

- Optical scatter from bubbles is transient in space and time. Optical scatter can be O(10) m^{-1} or more. The relevant space scales of the collections of bubbles that result from wave breaking are O(1)m over the range of wind speeds studied (maximum of ~10ms^{-1}).
- Optical scattering resulting from active breaking waves is relatively spectrally flat, with the dominant bubble sizes contributing to optical scattering being 50-100 microns in size. Enhancement to the RSR in the blue-green will depend on the relative concentrations of the other water-borne optical constituents present. The phase functions of bubbles are inherently different than other optical constituents found in the ocean, with scatter in the forward direction much more significant.
- Results from the Monte Carlo modeling effort indicate that even small bubble clouds produce water leaving-radiances that are significant even in the near infrared spectral region and will impact algorithms which assume zero water leaving radiances at this wavelength

- Monte-Carlo modeling efforts indicate that the horizontal and vertical gradients in the bubble field result in a heterogeneous light field which can not be reproduced by slab models which assume homogeneous horizontal distributions of IOPS.
- Monte-Carlo simulations suggest that interpretation of values of beam attenuation using commonly available instruments may be in error up to 50% in highly scattering environments. The error due to multiple scattering is estimated to be only a few % in media of O(100) m^{-1}.
- To completely remove sky reflection from above water measured light fields over small footprints will require a measurement of the 2-D wavenumber spectrum of the capillary-gravity waves which are responsible for reflecting the light (amplitude and phase), a measured distribution of the sky radiance field, and a complete model of photon propagation from the sun to the receiver. Without this information, extracting subtle signatures such as dilute bubble populations which are transient in time will prove difficult. We anticipate that at higher wind speeds, the ability to resolve the bubbles would be much easier. Unfortunately, the winds only briefly exceeded 10 ms^{-1} at the Hawaii study site – uncharacteristic for the season.

IMPACT/APPLICATIONS

The discrimination between Case 1 and Case 2 waters loses its meaning if we recognize that the scattering properties of near-surface waters can be largely determined by gas bubbles whose concentration and size distribution (i.e. major determinants of optical scattering) vary greatly in time and space as a function of wind and wave conditions. Consequently, one can argue that even Case 1 waters, do not exist in the top few meters of the ocean which are the most important for remote sensing of ocean color. Part of the error in the data products generated by the existing ocean color algorithms can certainly be attributed to variable concentration of gas bubbles submerged in the near surface layers. As an example, the existing parameterizations of backscattering coefficient in the semi-analytical algorithms for inverting reflectance measurements will most likely be biased by the presence of the sea state dependent bubble backscatter. In addition, submerged bubbles can influence the validation of the atmospheric correction, which is based on the comparison of in situ and satellite-derived water-leaving radiances. The quantification of these errors at the present time is, however, impossible because no simultaneous data exist that characterize optical properties and bubble populations in the water. It is anticipated that results of this research will provide an indication of these errors. Furthermore, we expect that the results of the research will provide opportunities in the future for remotely sensing air-sea interaction processes using hyperspectral optical techniques.

TRANSITIONS

Discussions with several DOD labs and contractors have taken place as bubbles are increasingly being recognized as an important optical constituent in VSW scenarios. Insight gained on our analysis efforts relating surface roughness to remote sensing reflectance should also be of interest to the applied community.

PUBLICATIONS IN DIRECT RESPONSE TO THIS PROGRAM

Piskozub, J., D. Stramski, E. J. Terrill, and W. K. Melville. 2004. Influence of forward and multiple light scatter on the measurement of beam attenuation in highly scattering marine environments. *Applied Optics*, 43, 4723-4731

Mobley, C. D., D. Stramski, W. P. Bissett, and E. Boss. 2004. Optical modeling of ocean waters: Is the Case 1 - Case 2 classification still useful? *Oceanography*, 17(2), 60-67.

Boss, E., D. Stramski, T. Bergmann, W. S. Pegau, and M. Lewis. 2004. Why should we measure the optical backscattering coefficient? *Oceanography*, 17(2), 44-49.

Terrill, E., Lewis, M. 2004. Tiny Bubbles: An Overlooked Optical Constituent Oceanography. *Oceanography*, 17(2), 11.

Stramski, D., E. Boss, D. Bogucki, and K. J. Voss. 2004. The role of seawater constituents in light backscattering in the ocean. *Progress in Oceanography*, 61, 27-56.

Piskozub, Jacek; Stramski, Dariusz; Terrill, Eric; Melville, W. Kendall - 3-D RADIATIVE TRANSFER MODELING OF THE EFFECT OF BUBBLE CLOUDS ON REMOTE-SENSING REFLECTANCE. Ocean Optics XVI. 2002

Terrill, Eric; Melville, Ken; Stramski, Dariusz – Influence of bubbles on marine optical properties. Ocean Optics XVI. 2002

Terrill, E.J., W.K. Melville, and Stramski, D. 2001 Bubble Entrainment by Breaking Waves and their Influence on Optical Scattering in the Upper Ocean. J. Geophys. Research. 16,815 - 16,823.

Terrill, E.J., W.K. Melville, and Stramski, D. 1998. Bubble Entrainment by Breaking waves and their Effects on the Inherent Optical Properties of the Upper Ocean. SPIE Ocean Optics OOXIV, Kona, HI. November 1998.

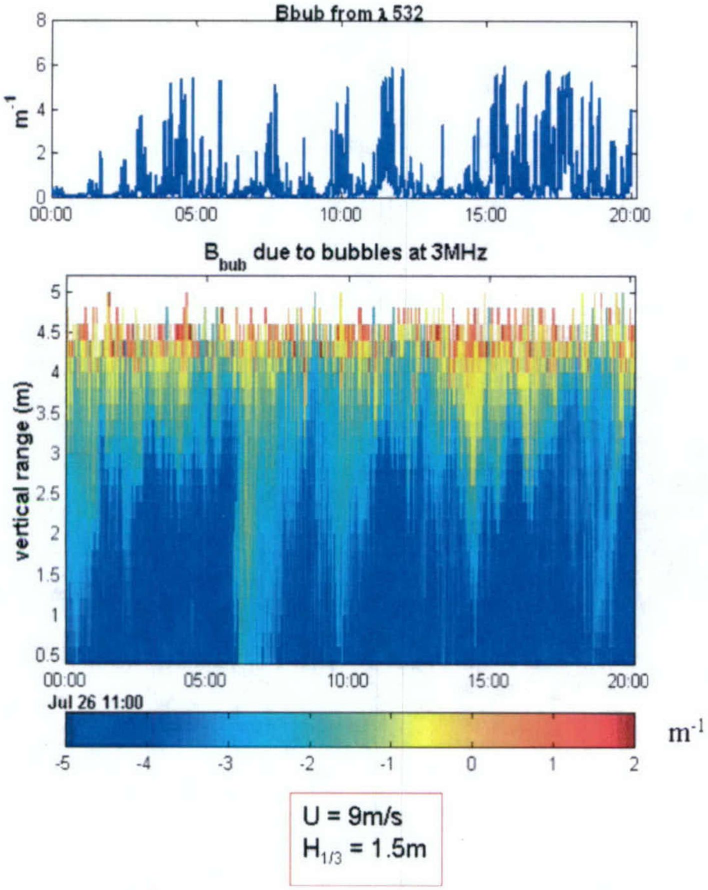

Figure 1. Top. Time series of optical scatter at 1m depth measured at 532nm from a buoy deployed at the LEO site during HYCODE. The time series shows the large fluctuations in scatter that are caused by intermittent injections of bubbles. Bottom. A time series showing the depth dependence of the bubble mediated scatter as a function of time and depth. These values of optical scatter were computed using high frequency (3MHz) sound and the geometric similarities between optical and acoustic scatter. The figure illustrates the intermittency and depth variability of the bubble field. The data shown was for a time period that had winds at 9 m/s and a significant wave height of 1.5m.

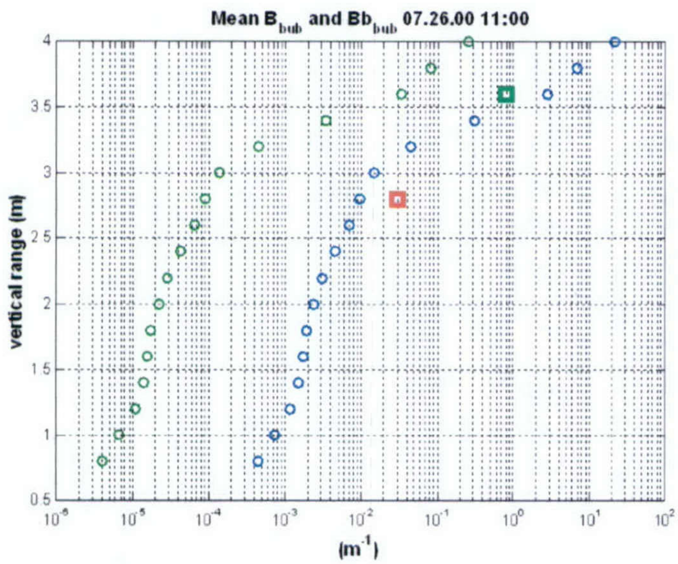

Figure 2. The depth dependence of the light scattering properties of the water due to bubbles. The profile shown was obtained using range gated acoustic techniques (circles) and is representative of the data shown in figure 1. The two squares are values measured by optical instruments and are consistent with the values based upon the acoustic data.

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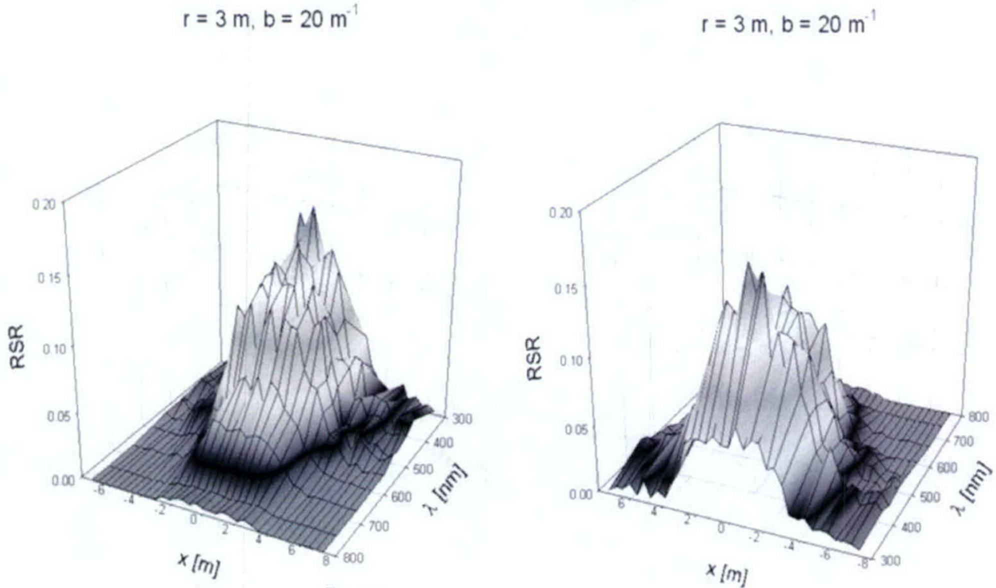
Remote sensing reflectance of a 3m radius x 2m deep 'bubble cylinder'

IOPs set corresponding to a Case 1, C = 0.5 mg/m^3 chlorophyll concentration

15m x 15m grid



Results:

* non-zero RSR at the reds

* the RSR does not reach spatial convergence over small length scales of IOP variability

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In this Monte Carlo simulation, the IOPs were set to a Case 1 situation based upon C = 0.5 mg/m^3 chlorophyll concentration. The computations were computed over a 15m x 15m grid and the total scattering was fixed for 20 m^{-1}. The results of the computations show a) there is a non-zero remote sensing reflectance at the red wavelengths, b) the remote sensing reflectance does not spatially converge over small length scales of IOPs. If convergence did occur, the RSR values would have 'flat tops' near in the regions defined by the geometry of the bubble cloud.

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